

Recent Paleolimnology of Upper Klamath Lake, Oregon

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Submitted to the

U. S. Bureau of Reclamation
Klamath Falls, Oregon

By

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Roseburg, Oregon

March 16, 2001

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ABSTRACT

Sediment cores were collected from Upper Klamath Lake in October, 1998 and analyzed for ^{210}Pb , ^{14}C , ^{15}N , N, P, C, Ti, Al, diatoms, *Pediastrum*, and cyanobacterial akinetes. These results were used to reconstruct changes in water quality in Upper Klamath Lake over the last 150 years. The results showed that there was substantial mixing of the upper 10 cm of sediment, representing the previous 20 to 30 years. However, below that, ^{210}Pb activity declined monotonically, allowing reasonable dating for the period from about 1850 to 1970. The sediment accumulation rates (SAR) showed a substantial increase in the 20th century. The increase in SAR corresponded with increases in erosional input from the watershed as represented by the increases in sediment concentrations of Ti and Al. The upper 20 cm of sediment (representing the last 150 years) also showed increases in C, N, P, and ^{15}N . The increases in nutrient concentrations may be affected to various degrees by diagenetic reactions within the sediments, although the changes in concentrations also were marked by changes in the N:P ratio and in a qualitative change in the source of N as reflected in increasing $\delta^{15}\text{N}$. The diatoms showed modest changes, particularly in the upper sediments, with increases in *Asterionella formosa*, *Stephanodiscus hantzschii*, and *S. parvus*. *Pediastrum*, a green alga, was well-preserved in the sediments and exhibited a sharp decline in relative abundance in the upper sediments. Total cyanobacteria, as represented by preserved akinetes, exhibited only minor changes in the last 1000 years. However, a taxon which was formerly not present in the lake 150 years ago, *Aphanizomenon*, has shown major increases in recent decades. Although the mixing in the upper sediments prevents high-resolution temporal analysis of the recent history (e.g. last 30 years) of Upper Klamath Lake, the results demonstrate that major changes in water quality likely have occurred leading to a major modification of the phytoplankton assemblage. The changes in sediment composition are consistent with land use activities during this period that include substantial deforestation, drainage of wetlands, and agricultural activities associated with livestock and irrigated cropland.

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INTRODUCTION

Upper Klamath Lake is an hypereutrophic lake in southern Oregon. This is the largest natural lake in the state ($\sim 275 \text{ km}^2$) and has been monitored and investigated numerous times over the last three decades (Kier Associates 2000; Brownell and Rinaldo 1995). The lake is located in a grabben on the east side of the Cascade Range east of Mt. McLoughlin and south of Crater Lake. Upper Klamath Lake is shallow with a maximum depth of 15.2 m (Johnson et al. 1985) and an average depth of 2.2 m (USBR 1997).

Although currently classified as hypereutrophic, there is considerable controversy regarding the historical condition of the lake prior to watershed development activities initiated by Euro-Americans beginning in the mid- to late 1800s. Previous investigations have shown that the lake has been productive for thousands of years (Sanville et al. 1974). This view of the lake as a naturally hypereutrophic system (Johnson et al. 1985) is consistent with its shallow morphometry, deep organic-rich sediments, and a large watershed with phosphorus-enriched soils. However watershed development, beginning in the late-1800s and accelerating through the 1900s, is strongly implicated as the cause of its current hypereutrophic character (Bortleson and Fretwell 1993).

Under current hypereutrophic conditions, the lake exhibits many water quality problems typically associated with excessive algal production. These include extended periods of low dissolved oxygen, elevated pH, and toxic levels of un-ionized ammonia, and previously productive fisheries are now subject to fish kills and water quality stress (Kann and Smith 1999; Perkins et al. 1999). Two fish species, the shortnose sucker (*Chasmistes brevirostris*) and Lost River sucker (*Deltistes luxatus*) were listed as endangered under the Endangered Species Act in 1988. Water quality degradation resulting from algal blooms had been identified as a probable major factor in their declines (Williams 1988). Moreover, based on harmful levels of dissolved oxygen, pH, and chlorophyll (algal biomass), the lake has been designated as water quality limited for resident fish and aquatic life (ODEQ 303(d) List 1998). Algal production in Upper Klamath Lake is now due almost entirely to extreme levels of the cyanobacterium (blue-

green alga) *Aphanizomenon flos-aquae*, which can account for more than 95% of the algal biomass occurring during the June through October growing season (Kann 1998).

Despite relatively low precipitation for the area (the watershed for Upper Klamath Lake lies in the rain-shadow of the Cascade Range), early Euro-American settlers took advantage of the numerous streams and rivers supplied by snow-melt and groundwater to provide irrigation water for livestock and crops, as well as of the extensive forests in the surrounding mountains to provide abundant supplies of timber to local mills. Timber harvest in the area was most active from 1925 to 1945, reaching a maximum production in excess of 800 MBF (Figure 1). Timber production has since stabilized near 400 MBF. Extensive wetlands, many adjacent to Upper Klamath Lake and Agency Lake, were drained to provide rich farmlands to support livestock and create cropland. Cattle production in the area reached a peak near 1960 with a total of about 140,000 head of livestock in the area (Figure 2). Cattle production is currently near 100,000 head. The Environmental Protection Agency (EPA Index of Watershed Indicators 1998) indicates that at least 110,000 acres of the watershed have been converted to irrigated pasture or other agricultural activities, and Risley and Laenen (1999; Fig. 18) show an 11 fold increase in permitted irrigated land acreage between 1900 and the present. Drainage of wetlands has been a relatively steady activity throughout the first 80 years of the 20th century (Figure 2), and studies indicate that large quantities of nutrients were liberated from these areas and subsequently pumped to the lake or its tributaries (Snyder and Morace 1997). Additional lake-related factors of note include changes to the lakes hydrology through water diversions of tributaries entering the lakes, by diversion of water out of the lake, and by the construction of the Link River Dam at the lake's outlet in 1921. As a result, both the timing and quantity of lake flushing flows and nutrient retention dynamics have been altered, and lake surface elevation and volume are reduced below the historical minimum pool level.

The current study was initiated to assist in better understanding the historical conditions in Upper Klamath Lake through application of more recent advances in

paleolimnological techniques. In addition to the use of diatoms to evaluate changes in water

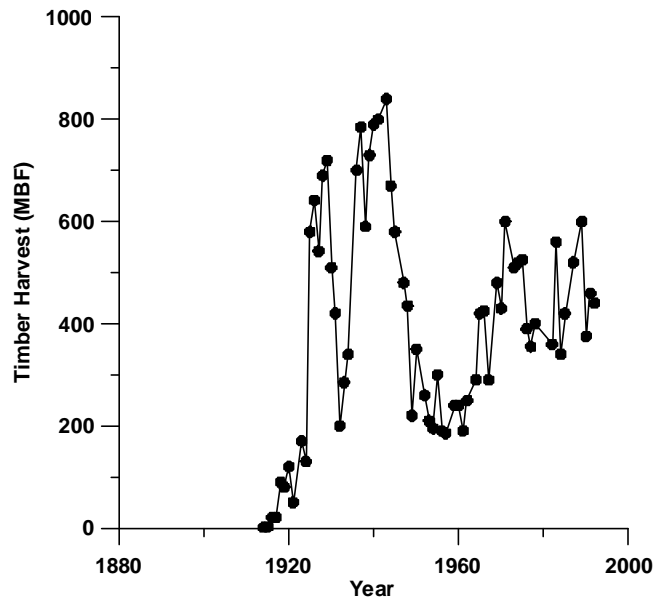


Figure 1. Timber harvest in Klamath County, Oregon, in millions of board feet (MBF). Values represent the sum of production from public (Winema National Forest), private, and Klamath Tribes domains. Redrawn from Risley and Laenen (1999)

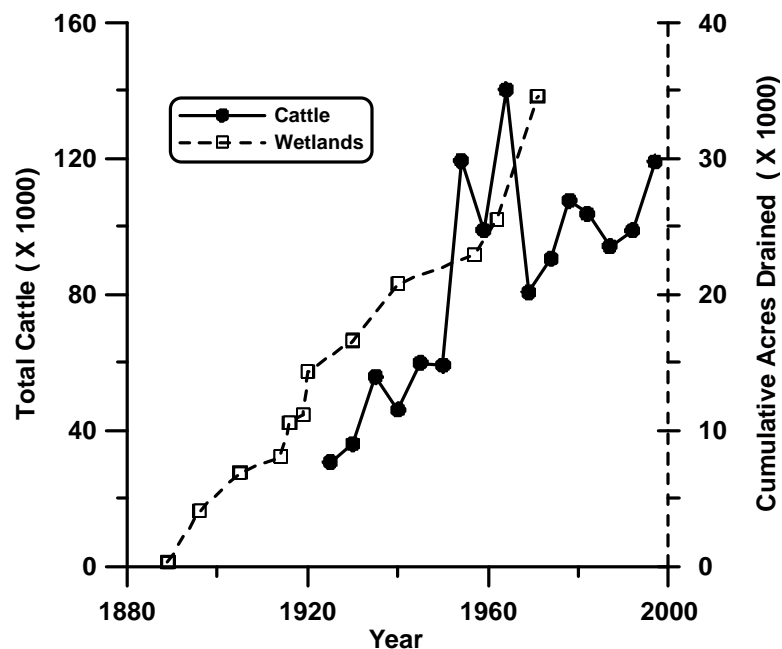


Figure 2. Cattle production (?) in Klamath County, Oregon derived from U.S Dept. Commerce. Values represent the sum of both dairy and non-dairy cattle

production. Cumulative acres of wetlands drained (?) in Klamath County. Data compiled by Gearheart et al. (1995) and Snyder and Morace (1997).

quality, we also measured metals to determine relative changes in sources of sediment, nutrients and natural isotopes of nitrogen to evaluate changes in sources of nutrients, and remains of cyanobacteria and chlorophyta to determine changes in phytoplankton species composition not reflected in the diatom analyses.

METHODS

Upper Klamath Lake sediments were collected on October 21, 1998. Three sediment cores were collected, two with a 10 cm diameter gravity corer and one with a 5 cm diameter piston corer. Coring locations were chosen, in part, to minimize the effects of wind-induced resuspension of sediments (Laenen and Le Tourneau 1996). One site was located north of Shoalwater Bay and two sites were located south of Bare Island. All cores were collected from lake depths of about 4m. Locations of the sediment cores are illustrated in Figure 3. A 10 cm-diameter corer, equipped with a sphincter device to close the base of the core, was slowly lowered into the sediments using a motorized winch mounted on a crane attached to the boat. The sphincter was closed prior to retrieving the sediment core. Sediment samples were extruded and placed in Whirlpac[®] bags in a cooler and returned to Corvallis where they were refrigerated. Subsamples of the sediment (not the elutriate) were analyzed for ¹⁴C, ²¹⁰Pb, percent water, C, N, S, P, Ti, Al, diatoms, *Pediastrum*, and cyanobacterial akinetes. Carbon, nitrogen, and sulfur were analyzed using a Leco model CNS-2000 elemental analyzer. Standard Leco operating procedures were followed using sulfamethazine for standardization and a combustion temperature of 1350° C. Other elements were analyzed with a Perkin Elmer Optima 3000 DV ICP spectrometer using the radial view. Samples were first digested in a CEM Corporation model MDS-2000 microwave digestion oven. A total digest of the sediment (CEM Corp. 1991) using HNO₃, HF, HCl, and H₃BO₄ was used for the analysis of P, Ti, and Al.

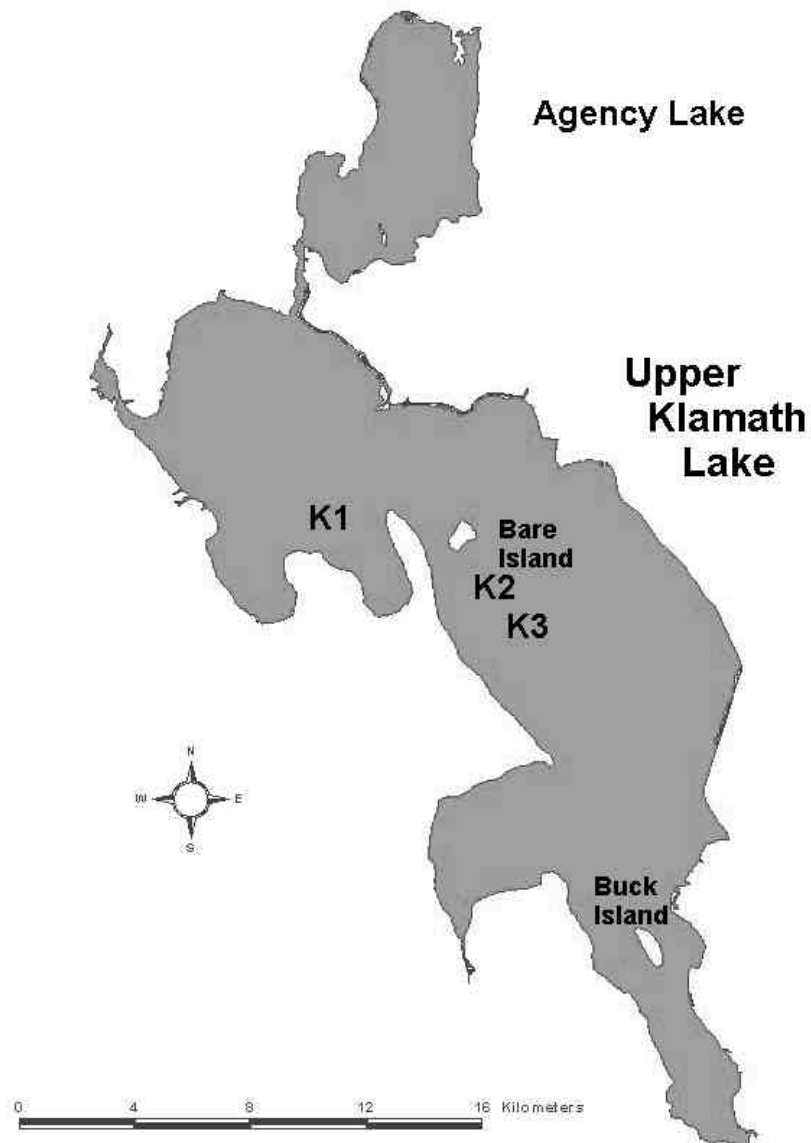


Figure 3. Upper Klamath Lake, Oregon showing the locations of the sediment collection sites. Core K1 is the primary core used in this analysis.

Isotopic analysis of sediments for ^{15}N was conducted at the Stable Isotope Research Unit at Oregon State University, Corvallis, OR. The sediment samples were analyzed with a Roboprep C/N analyzer linked to a 20-20 Isotope Ratio Mass Spectrometer. The system utilizes a Dumas combustion/reduction apparatus. The reported precision for this unit is ± 0.3 parts per thousand.

Sediment samples were dated using ^{14}C and ^{210}Pb isotopes. ^{14}C was analyzed using accelerator mass spectrometry (AMS) by Lawrence Livermore Nuclear Laboratory through Beta Analytic, Inc. The material was pre-treated with HCl washes to strip the sediments of carbonates. ^{210}Pb was analyzed using alpha spectroscopy (Eakins and Morrison 1978), which involves distillation of the sample, HNO_3 digestion, and plating onto silver prior to counting. The sediment ages and accumulation rates were calculated using the constant-rate-of-supply (CRS) model of Appleby and Oldfield (1978) with old age dates using the method described by Binford (1990).

Preparation of diatom samples followed standard procedures outlined by Battarbee (1986). Briefly, between 2.00-4.83g of sediment were mixed with concentrated sulphuric and nitric (50:50 molar) acid. After washing, an aliquot of the remaining slurry was evaporated onto cover slips. Cover slips were then permanently mounted onto glass slides with Naphrax®. Approximately 600 (595-1068) diatom valves were identified and enumerated along transects. Total numbers of diatoms counted varied because counting was usually completed at the end of a transect or halfway through a transect. Counting was done under oil immersion using a Nikon Eclipse E600 microscope equipped with differential interference contrast optics (1,250 X magnification; N.A. = 1.4). The taxonomy and nomenclature follows: Patrick and Reimer (1966; 1975), Krammer and Lange-Bertalot (1986-1991) and Cumming et al. (1995).

Slides for enumeration of akinete and *Pediastrum* counts were prepared by diluting a 1 mL subsample of the lake sediments to 20 mL. From this diluted subsample, 0.25 mL was permanently mounted in HPMa using a modification of Crumpton (1987) and St. Amand (1990). *Aphanizomenon* akinetes, pollen grains, and *Pediastrum* colony remnants

were counted on an Olympus BH-2 research grade compound microscope equipped with Nomarski optics and epifluorescence and a 1.25 multiplier. Cells, grains, and colony remnants were visualized using blue-light epifluorescence at 400X. Between 300 to 400 random fields were spread evenly over three slide mounts per sample. In the case of colony remnants, cells per colony were also tabulated.

RESULTS

1. Sediment Dating and Sediment Accumulation Rates

Sediment from the base of two of the three cores was aged using ^{14}C methodology. The measured ^{14}C age was 1420 (\pm 40) YBP (years before present) in core K1 for interval 65-66cm. This corresponds to a calibrated radiocarbon date of 550 to 665 AD. For core K2 at interval 64-66 cm, the measured age was 1460 (\pm 40) YBP. This corresponds to a calibrated radiocarbon date of 530 to 650 AD. The results for the two separate cores are not significantly ($P = 0.05$) different from one another and show that for these two sites, the gross rates of sediment accumulation are approximately the same.

The primary focus of this project was on changes in Upper Klamath Lake that may have occurred in the last 100 to 150 years. The sediment in core K1 and K3 were dated using ^{210}Pb methodology, which provides information on sediment age for the period of interest. The results for the two cores are presented in Figures 4 and 5. The measured ^{210}Pb concentrations in the two cores agree closely. The supported concentrations are noteworthy because of the extremely low values at about 0.003 Bq/g. Total and excess ^{210}Pb values are also low, well below the concentrations expected from atmospheric fallout.

Sediment accumulation rates (SAR) calculated from the ^{210}Pb measurements are presented in Figures 6 and 7. The general rates of accumulation in both cores are comparable and range from about 10 to 200 $\text{g}/\text{m}^2/\text{yr}$. The average rates of accumulation for depths deeper than 10 cm were 50 (\pm 32) $\text{g}/\text{m}^2/\text{yr}$ in core K1 and 30 (\pm 12) $\text{g}/\text{m}^2/\text{yr}$ in core K3. The SAR values for core K3 were more erratic than for core K1 consequently, the remaining analyses were focused on core K1. The rates of sediment accumulation appear to increase throughout the period datable with ^{210}Pb . Accumulation rates increase at a lower rate in the lower sediments and accelerate to substantially greater values in the upper sediments. The overall rate of sediment accumulation appears to have

increased about six-fold, using a baseline rate of 20 g/m²/yr at 20 cm to 120 g/m²/yr as an average rate for the upper 10 cm.

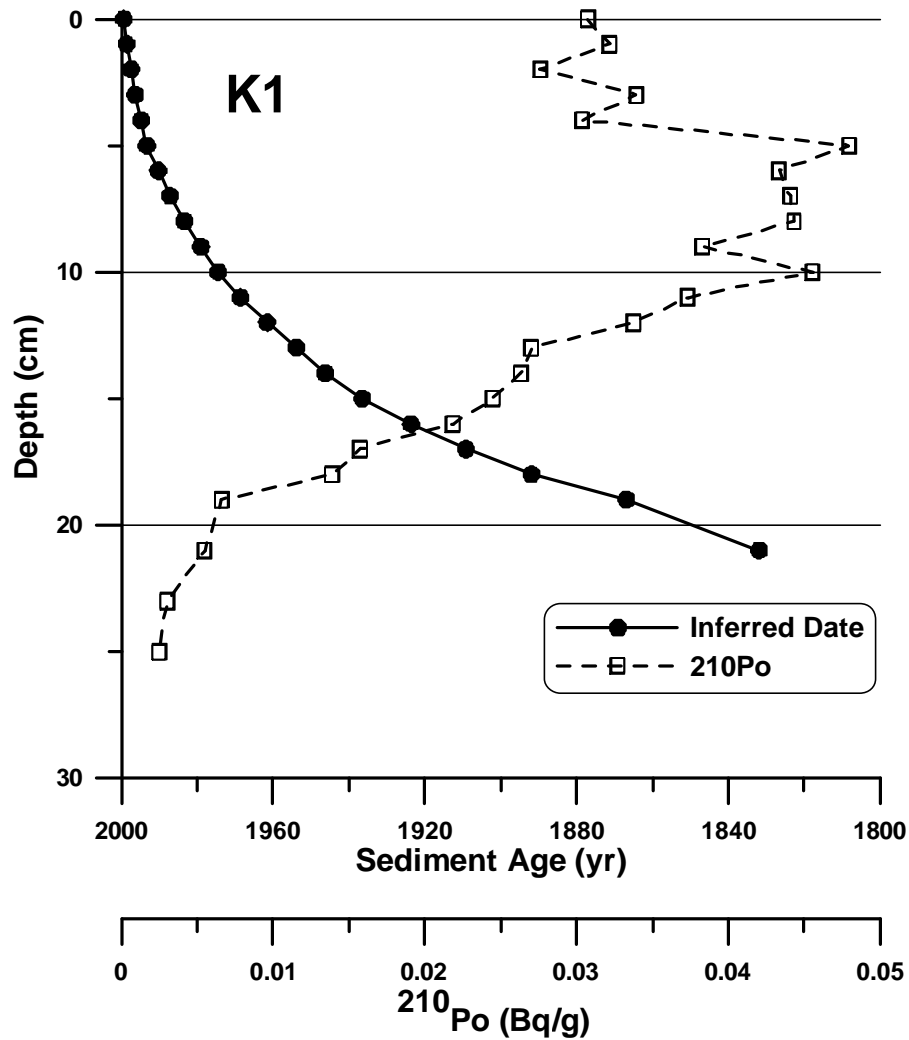


Figure 4. Measured ²¹⁰Po activity (□) in Core K1, Upper Klamath Lake versus sediment depth. Modeled age of sediments (●) using the CRS model (Appleby and Oldfield 1978).

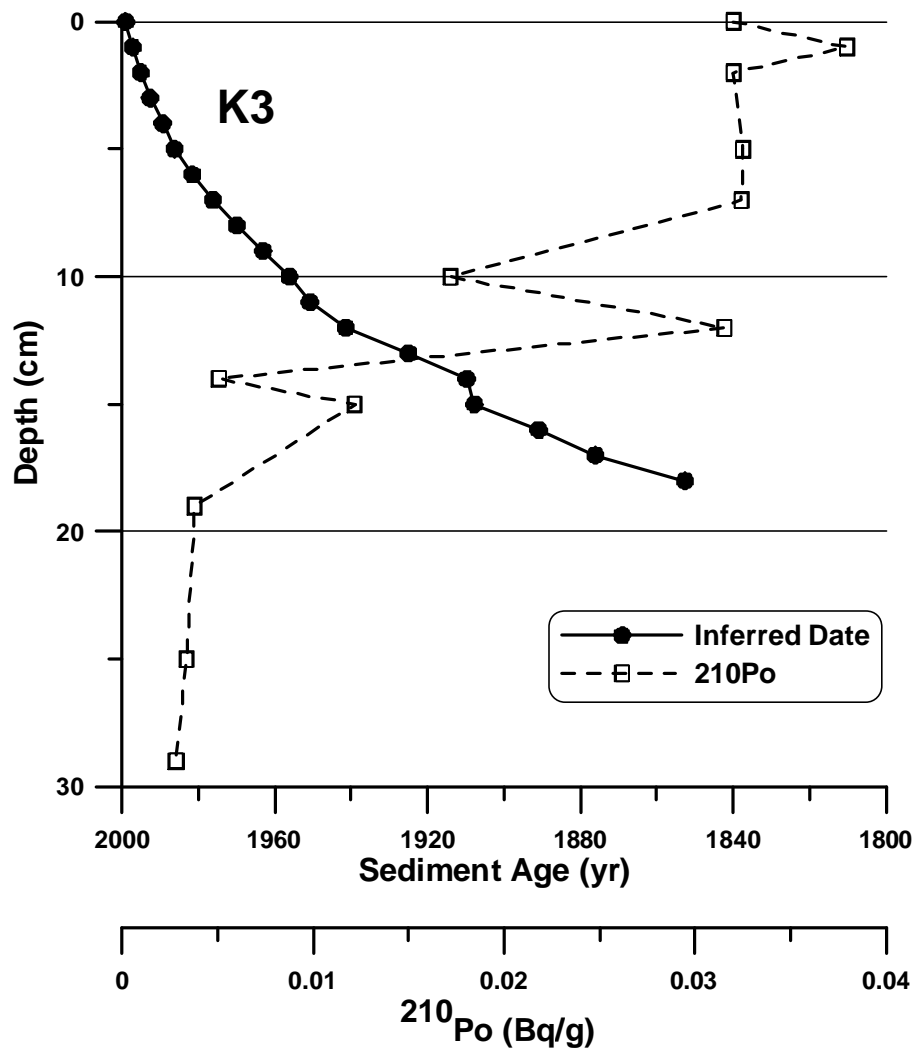


Figure 5. Measured ^{210}Po activity (Bq/g) in Core K3, Upper Klamath Lake versus sediment depth. Modeled age of sediments (yr) using the CRS model (Appleby and Oldfield 1978).

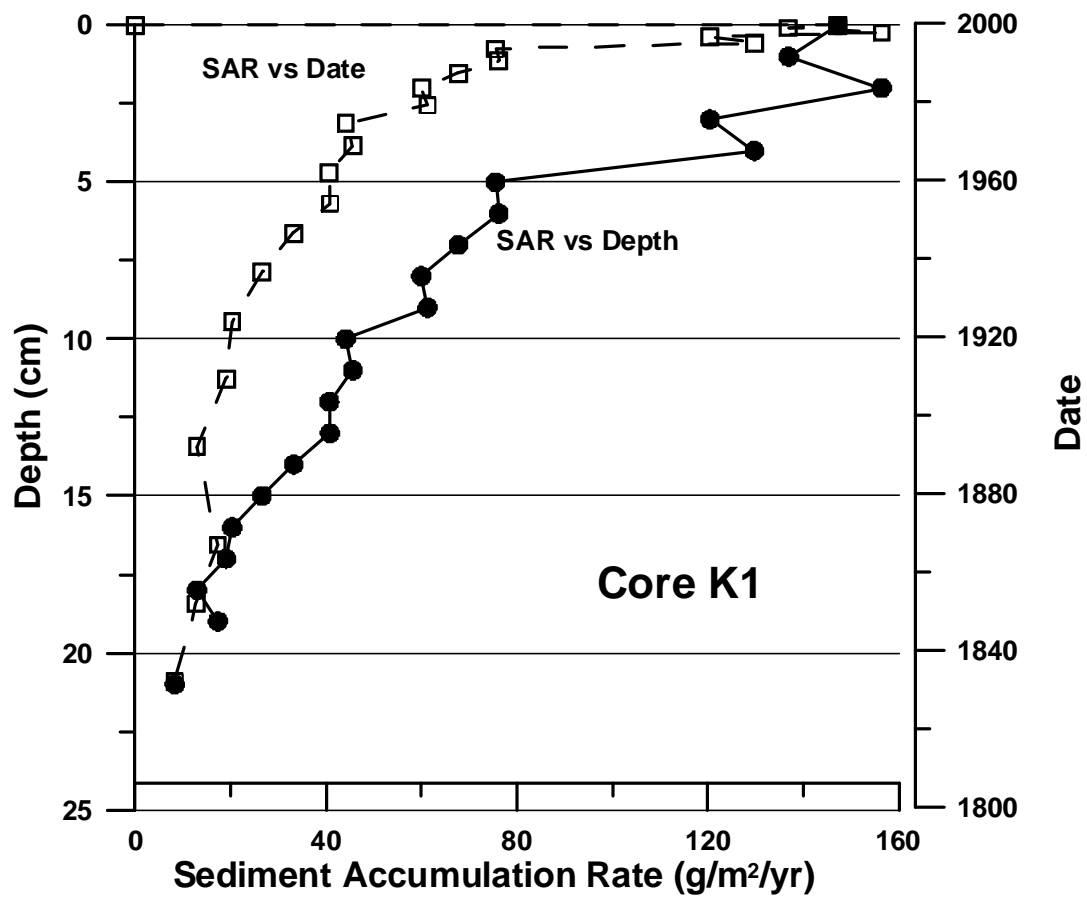


Figure 6. Calculated sediment accumulation rates (SAR) for Core K1 plotted versus date (?) and sediment depth (?).

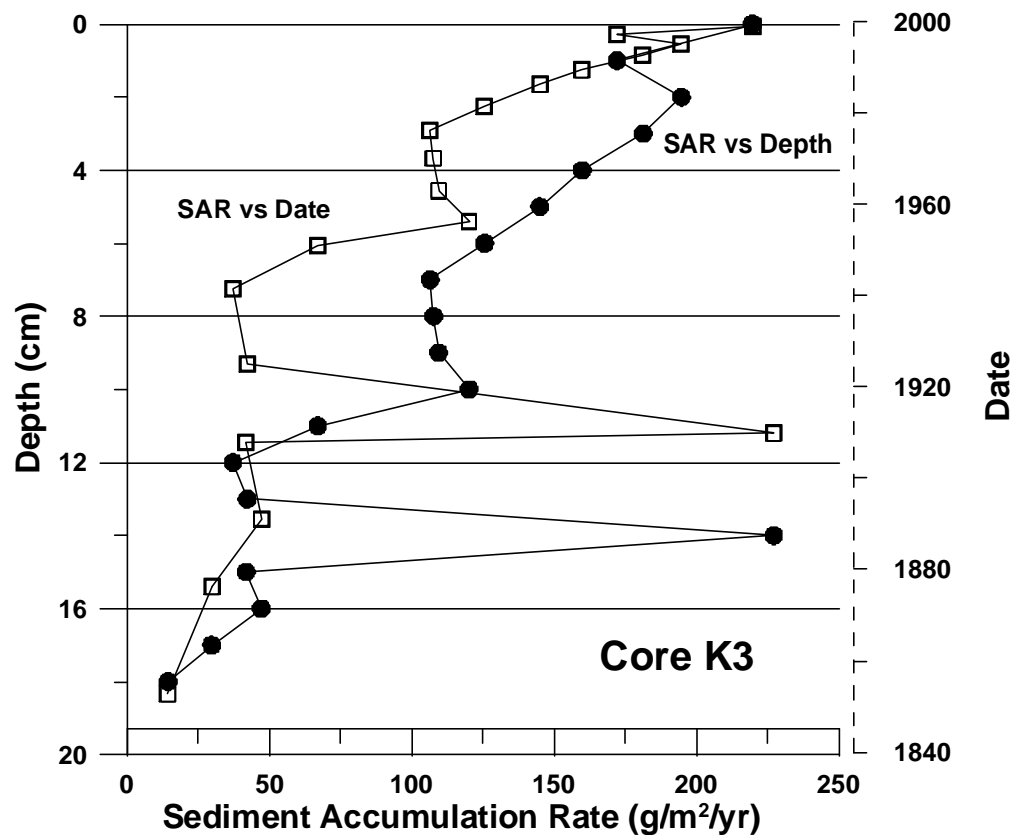


Figure 7. Calculated sediment accumulation rates (SAR) for Core K3 plotted versus date (?) and sediment depth (?).

2. Sediment Composition

a. Water Content

Water content in the sediment was high ranging from 87 % to over 94% at the sediment-water interface (Figure 8). However, unlike many lake sediments that exhibit a monotonic decline in water content, the sediment in Upper Klamath Lake display a rapid initial decline in water content, followed by an increase for several centimeters before again resuming a relatively continuous decline.

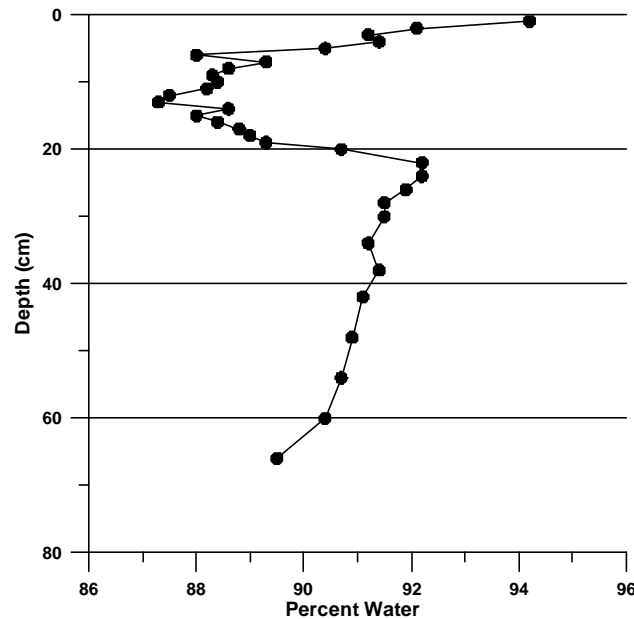


Figure 8. Water content of sediment in Core K1 versus depth in sediments

b. Nutrients

The sediments were analyzed for carbon (C), nitrogen (^{14}N , ^{15}N), and total phosphorus (P). The results shown in Figure 9 illustrate that the upper sediments are enriched in C, N, and P relative to concentrations measured in the lower sediment. The enrichment of the upper sediments ranged from about 20% for nitrogen to approximately 50% for phosphorus. Although both N and P increase in the upper sediments, the differences in

the rates of enrichment result in a significant alteration in the N:P molar ratio where the ratio is generally above 20 in the sediment below 17 cm and is less than 20 in the upper sediments (Figure 10). The heavier isotope of nitrogen (^{15}N) also was measured to assist in determining possible factors associated with the increase in total nitrogen. The results show a significant change in the proportion of ^{15}N in the upper sediments (Figure 11). Thus, there has been both an increase in the overall concentration of N in the upper sediments and a qualitative change in the source of nitrogen being deposited in the lake.

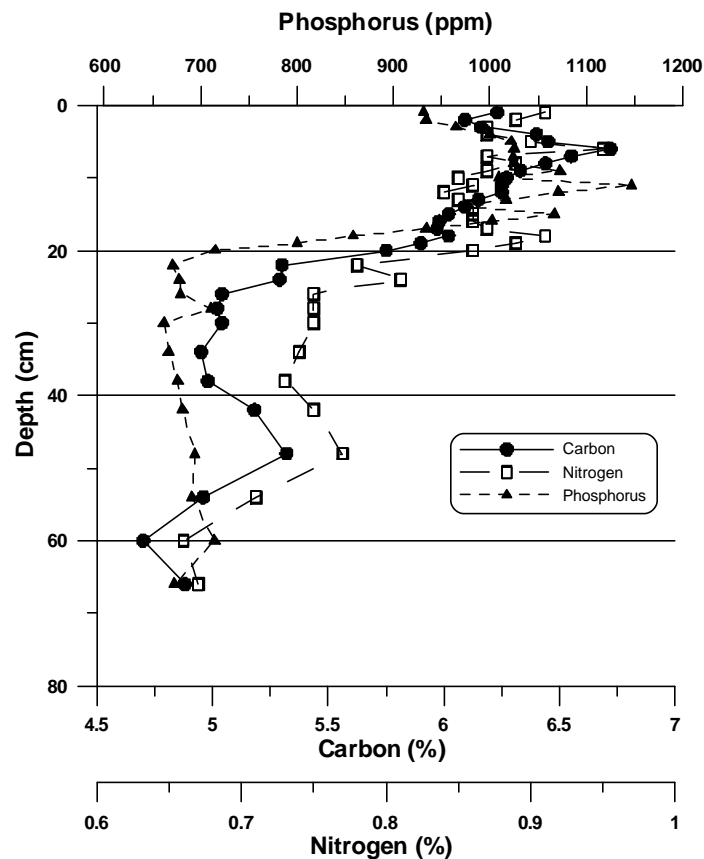


Figure 9. Concentrations of carbon (?), nitrogen (?), and phosphorus (?) for sediments in Core K1. Carbon and nitrogen are expressed as percent dry weight; phosphorus is expressed as parts per million dry weight.

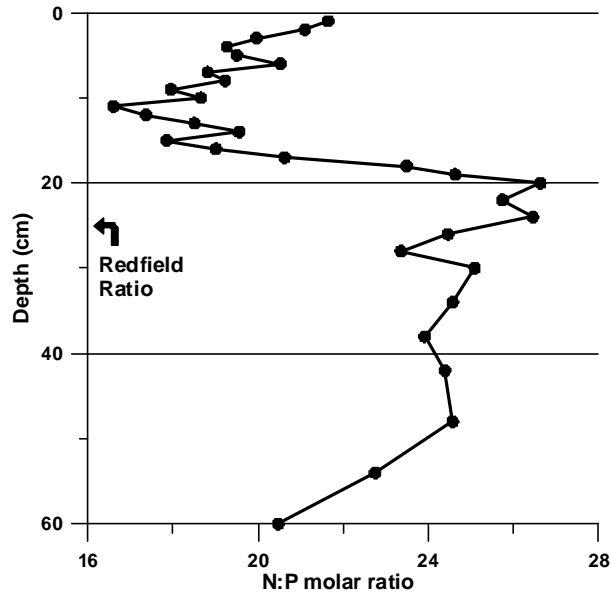


Figure 10. Atomic (molar) ratio of nitrogen to phosphorus in Core K1 versus depth in sediment. The expected N:P ratio for phytoplankton protoplasm is shown for reference (Redfield 1934).

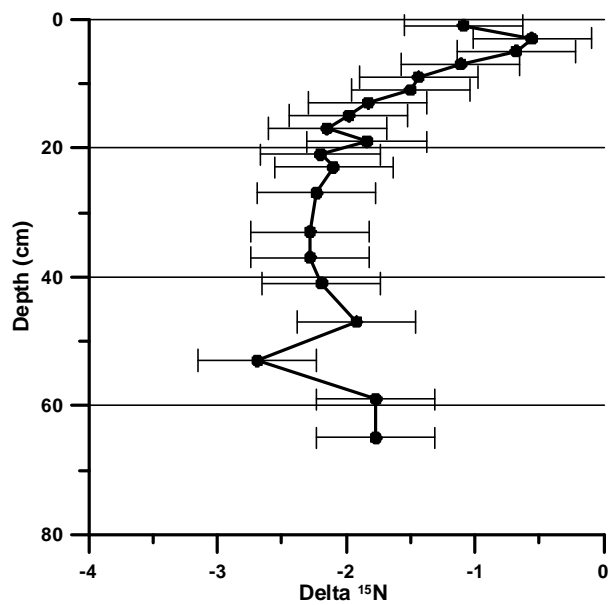


Figure 11. Delta ¹⁵N (‰) for sediments for Core K1.

c. Metals

Titanium (Ti) and aluminum (Al) were measured in the sediments to assess possible changes in the source material being deposited. Ti and Al are both used as indicators of erosional inputs from the watershed. Ti is particularly useful for this application because it is neither sensitive to redox conditions in the sediment nor is it incorporated into biological processes. Ti shows a 40% increase in the upper sediments, whereas Al exhibits an increase over 200% (Figures 12 and 13). The increase in Ti occurs from 20 to 10 cm, whereas the increase in Al occurs largely above 10 cm.

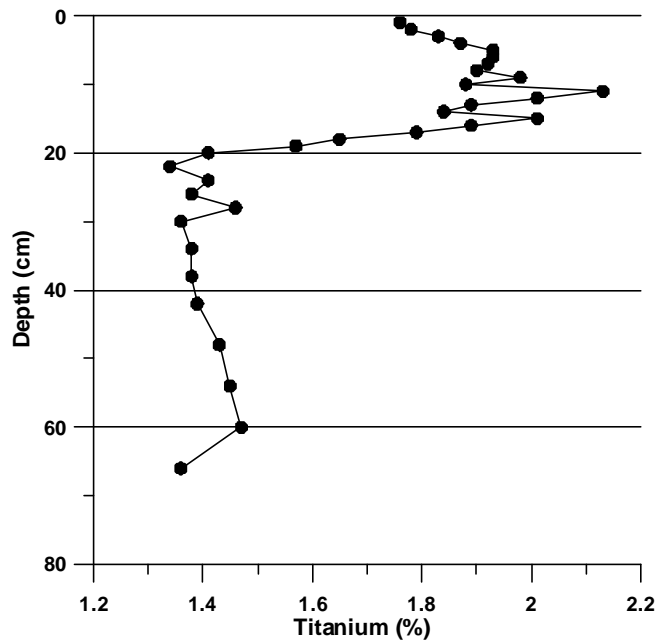


Figure 12. Titanium concentrations, expressed as percent dry weight, for Core K1

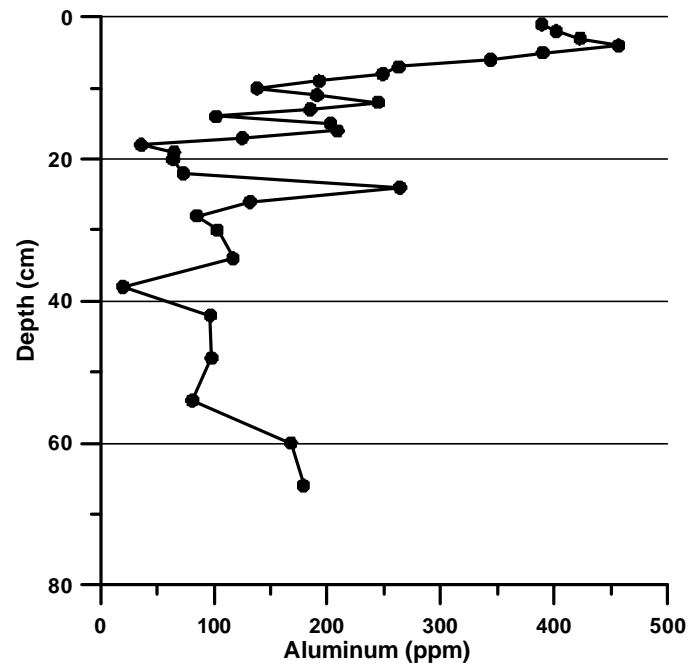


Figure 13. Aluminum concentrations, expressed as parts per million dry weight, for Core K1.

d. Diatoms

Several biological indicators of water quality in Upper Klamath Lake were analyzed to assess possible changes in the lake. The first group of organisms presented here are the diatoms (Class Bacillariophyceae; Division Chlorophyta). The dominant diatom taxa are illustrated in Figure 14. Three principal zones have been identified in the core: 1) Zone 1 (66-59.5cm); 2) Zone 2 (59.5-19cm), and 3) Zone 3 (19-0cm). Zone 3 has been further partitioned into two subsets.

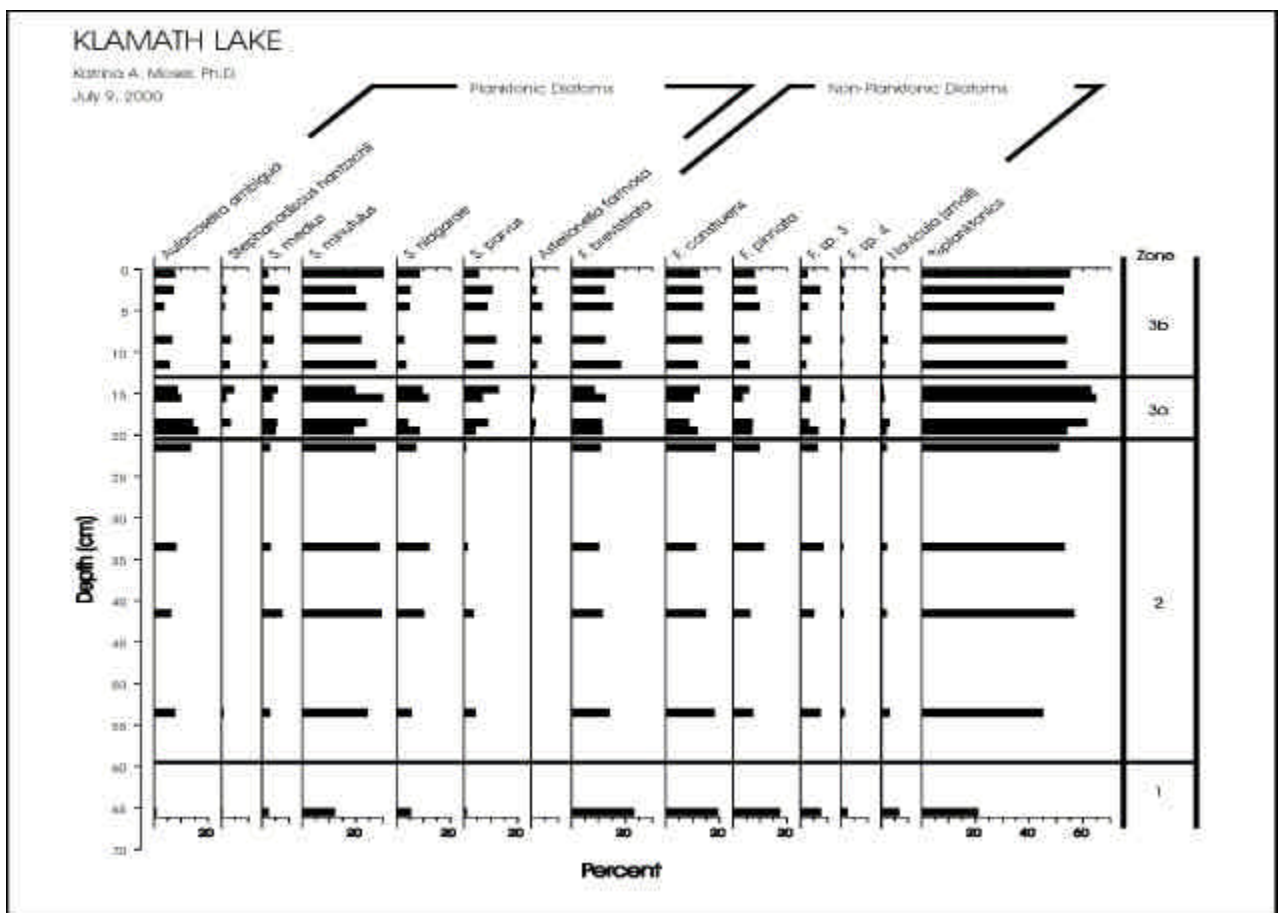


Figure 14. Dominant diatom taxa in the sediment for Upper Klamath Lake

Zone 1 (66-59.5cm)

Zone 1 is dominated by small benthic *Fragilaria* (~71%), including mainly *F. brevistriata* (~23%), *F. construens* (~19%), *F. pinnata* (~17%) and *F. sp. KL 3* (~7%). This zone also includes the highest abundance (~6%) of small *Navicula* diatoms (also non-planktonic), such as *N. absoluta*, *N. modica*, *N. minima*, *N. pseudoventralis*, small *N. pupula*, *N. submuralis* and *N. sp. KL 1* in this core. Planktonic diatoms only make up approximately 20% of zone 1, and are dominated by *Stephanodiscus* taxa, primarily *S. minutulus* (~12%). *Stephanodiscus medius*, *S. niagarae* and *S. parvus* occur in relatively small abundances (~2%, ~5% and 0.9%, respectively). Two unknown species of *Fragilaria* are also noted in relatively small percentages in this zone, *Fragilaria* KL sp. 3 (~7%) and *F. KL sp. 4* (~2%).

Zone 2 (59.5-20cm)

Zone 2 is mainly delineated by a sharp increase in planktonic diatoms from ~20% to ~51%. *Stephanodiscus minutulus*, *S. niagarae* and *S. parvus* increase (24%, ~9% and 4.2%, respectively) and *Aulacoseira ambigua* (~9%) appears for the first time. *Fragilaria brevistriata*, *F. construens* and *F. pinnata* all decrease at this time (~11%, ~16% and 9%, respectively). Small *Navicula* taxa and *Fragilaria* KL sp. 4 also decrease (~2% and ~0.7%, respectively).

Zone 3 (20-0cm)

The percentage of planktonic diatoms increases slightly to ~56% in this zone. Zone 3 has been subdivided into two subzones – Zone 3a and 3b. Zone 3a extends from 20-13cm, and is differentiated from Zone 2 by the first appearance of *Asterionella formosa* (~0.9%: Figure 15) and increases of *Stephanodiscus hantzschii* (~2%: Figure 16) and *S. parvus* (~8%: Figure 17) from close to 0% in zone 2. Slight decreases in *S. minutulus* (~23%) and small benthic *Fragilaria* also mark this zone. In particular, *Fragilaria construens* and *F. pinnata* decrease to ~11% and ~6%, respectively. *F. sp. KL3* also decreases to ~4%.

Zone 3b extends from 13-0cm, and is differentiated from Zone 3a by decreasing *Aulacoseira ambigua* (~6%) and *S. niagarae* (~5%). Several taxa increase slightly, including *Asterionella formosa* (~2%), *Fragilaria brevistriata* (~15%), *F. construens* (~11%) and *F. pinnata* (~6%).

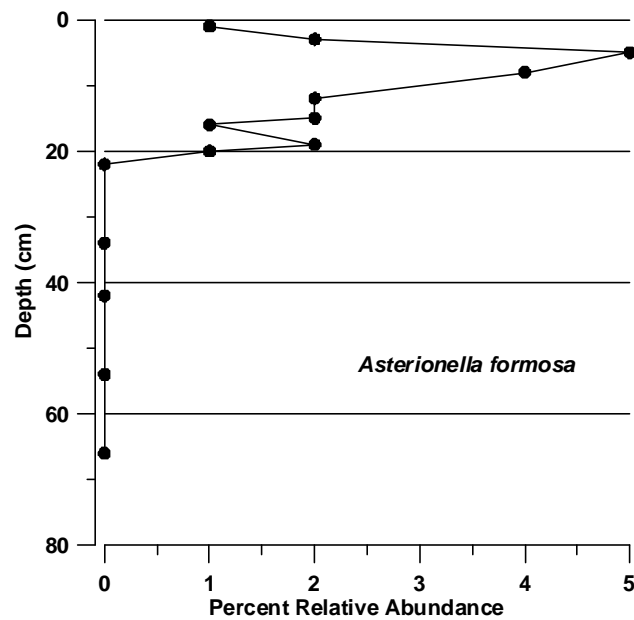


Figure 15. Percent relative abundance of the diatom, *Asterionella formosa*, Core K1.

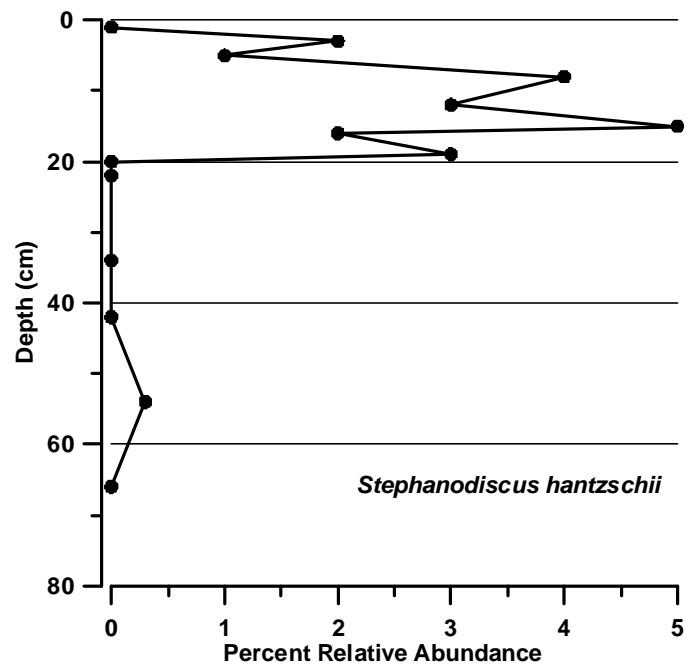


Figure 16. Percent relative abundance of the diatom, *Stephanodiscus hantzschii*, Core K1.

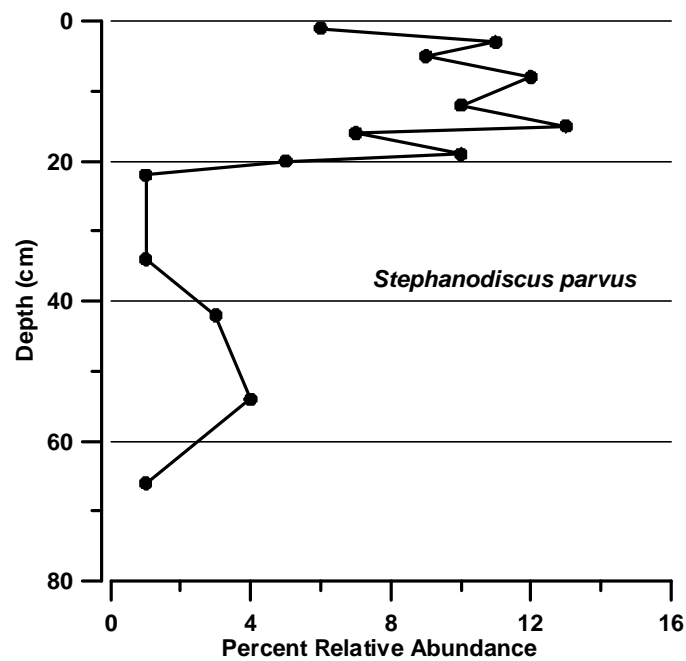


Figure 17. Percent relative abundance of the diatom, *Stephanodiscus parvus*, Core K1.

e. *Pediastrum*

Pediastrum is a genus of green (Chlorophyta) algae that leaves fossilized coenobia in lake sediments (Zippi 1998). The relative abundance of *Pediastrum* declined from about 95% (relative to akinete counts; although *Aphanizomenon* is the current dominant phytoplankton taxa in the surface waters, not all *Aphanizomenon* individuals form akinetes thus accounting for the apparent discrepancy in the relative abundances of the *Pediastrum* and *Aphanizomenon* in the sediments) in the lower sediments to below 80% in the surface sediments (Figure 18). Because the upper sediments have shown a major increase in SAR, the absolute counts of *Pediastrum* have increased overall but their proportion relative to other reference taxa has decreased significantly.

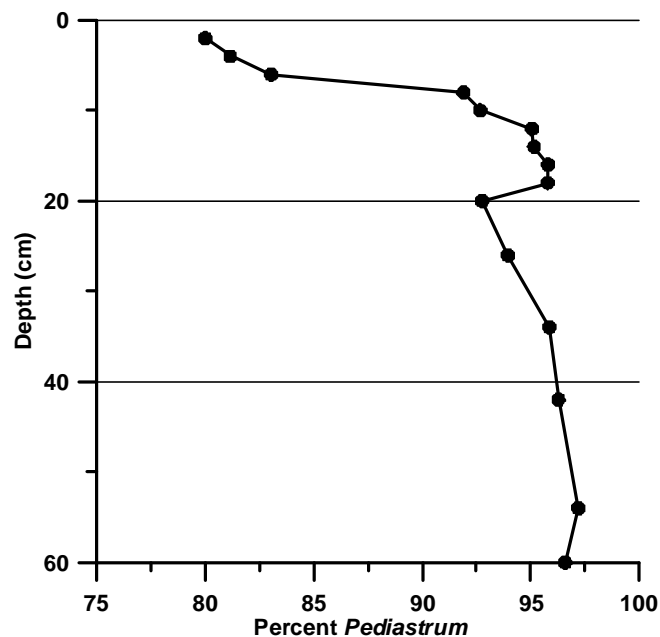


Figure 18. Relative abundance of green alga, *Pediastrum*, expressed as a percentage of *Pediastrum* + cyanobacterial akinetes

f. Cyanobacteria

The cyanobacterium (blue-green alga), *Aphanizomenon flos-aquae* is the dominant phytoplankton species in Upper Klamath Lake during the summer growing season (Kann 1998), and biomass levels are such that they support a major harvesting program used to manufacture food supplements (Carmichael et al. In Press). Although cyanobacteria normally decompose within the lake or the sediments, some species produce resting cysts, termed akinetes, which can remain preserved for thousands of years (*cf.* van Geel et al. 1994). Two types of akinete counts were conducted: total cyanobacterial akinetes and *Aphanizomenon* akinetes. The results show relatively small changes in the total abundance of preserved akinetes in Upper Klamath Lake, but *Aphanizomenon* akinete abundance has increased from complete absence in the sediments below 20 cm to over 8% (again, the 8% is relative to the counts of *Pediastrum* colonies and pollen grains) in the surface sediments (Figure 19). The increase in *Aphanizomenon* in the upper sediments is well represented ($r^2 = 0.96$) by the fitted equation shown in Figure 19.

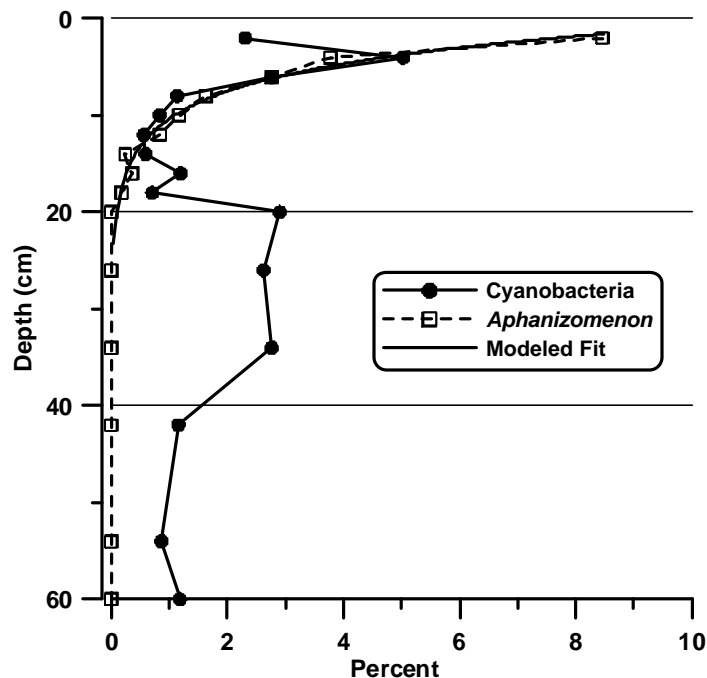


Figure 19. Relative abundance of *Aphanizomenon* (?) and non-*Aphanizomenon* cyanobacterial akinetes (?) in Upper Klamath Lake.

DISCUSSION

The dating of sediments in a shallow, productive system such as Upper Klamath Lake can be highly problematic due to wind-induced resuspension of sediments, diagenetic reactions causing gas generation, bioturbation from benthivorous fish, burrowing insect larvae, and detachment of surface sediment raised from the lake bottom by algal mats. Several previous attempts at dating the sediments in Upper Klamath Lake have yielded some useful results, although all investigators noted the existence of various degrees of mixing in the upper sediments. Sanville et al. (1974) measured ^{14}C in eight sediment intervals distributed among three different cores and concluded that sediment accumulation rates (SAR) had increased greatly in recent times. Martin and Rice (1981) measured ^{210}Pb activity in eight sediment cores collected from throughout Upper Klamath Lake and also concluded that SAR had increased in modern times.

The most recent study of the lake sediment, prior to our effort, was an extensive study of long-term rates of sediment chemistry and diatom stratigraphy conducted by the U.S. Geological Survey as part of larger effort to better understand climate change. Colman et al. (1999) measured ^{137}Cs , ^{210}Pb , and ^{14}C in three cores collected in various locations in the lake. Although the major focus of their effort was to conduct a long-term chronology for evaluation of climatic changes, they measured ^{137}Cs and ^{210}Pb to constrain the uncertainty in the ^{14}C dating. The extensive downcore analysis of ^{14}C by Colman et al. (1999) indicated that the carbon dating exhibited a positive bias of about 400 years. They attributed this to inputs of older organic material. The results for both cesium and lead showed that there was mixing of the upper sediments and mobilization of the cesium downcore. Similar to Martin and Rice (1981), Colman et al. (1999) presented the results as an average sedimentation rate for the surficial sediments (upper 20-25 cm). When we compare the results from Martin and Rice (1981) and Colman et al (1999) expressed as an average rate of sedimentation for the upper sediments (< 25 cm), we observe a high degree of similarity (Figure 20).

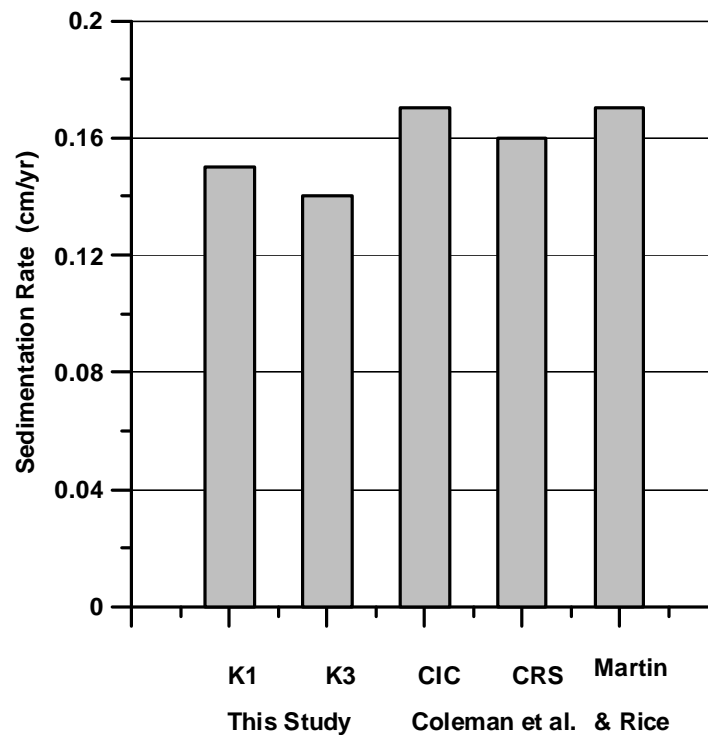


Figure 20. Average sedimentation rates calculated based on ^{210}Pb measurements in the upper sediments of Upper Klamath Lake. The rates from this study are shown for cores K1 and K3 (using the CRS model) compared to the median of three cores collected by Colman et al. (1999) [shown for both CIC and CRS models], and the median of eight cores collected by Martin and Rice (1981).

Thus, all three studies show that the upper 20 to 25 cm of sediment represents the most recent 150 years of accumulation. However, it is uncertain the degree to which the upper sediments can be distinguished with respect to specific dates or ranges of dates. Colman et al. (1999) report a mixing zone of about 8 cm thick. Our observations are consistent with this at about 10cm thick. The measured ^{210}Pb in the upper 10 cm corresponds with an activity level representing 20 to 30 years of ^{210}Pb . Therefore, if the mixing is instantaneous (i.e., associated with wind-induced mixing episodes) all of the reported ages in our cores are about 25 years too old. However, it is unlikely that the mixing is instantaneous which is supported by the results of other constituents such as the *Aphanizomenon* akinetes. Because other sediment constituents are not homogeneously mixed, the time constant for the mixing must be finite.

Therefore, although the mixing characteristics of Upper Klamath Lake contribute to uncertainty in the dating of recent sediments, the results show that the upper sediments can be partitioned into zones representing different periods of recent history. Under the most conservative of interpretations, the zones represent a 20th century versus pre-development. However, we believe that in the case of core K1, a more refined partitioning is supportable in which the 20th century can be distinguished as several zones of about 25 to 30 years in duration.

The sediment chemistry of Upper Klamath Lake, as characterized by core K1, shows an abundance of nutrients. The composition of the modern sediments (20th century) is enriched in both N and P compared to pre-settlement sediment. However, whether this pattern reflects differences in depositional history is uncertain. Upper Klamath Lake is subject to a high degree of physical mixing as previously described. In addition, diffusion and diagenetic reactions make it highly likely that redox-sensitive constituents are moved rapidly through these sediments. For example, Colman et al. (1999) attributed the peak of ¹³⁷Cs in the sediments at a depth of 19 cm to chemical mobilization downcore rather than a simple physical mixing process.

Despite the likelihood that considerable physical mixing and chemical transport occurs in the sediments, there are some intriguing patterns with respect to nitrogen and phosphorus in the sediments that warrant examination. As noted in the results, both N and P increase in the modern sediments. However, the rates of increase are quite different, resulting in a significant decrease in the N:P ratio in the upper sediments (Figure 10). If this pattern is not an artifact of post-depositional processes, then either the phosphorus loading to the lake has increased relative to the nitrogen loading, or the degree of N fixation from sources such as cyanobacteria has declined. Given the abundance of N-fixing cyanobacteria present in Upper Klamath Lake, it would appear more likely that the P loading has increased relative to N loading. A third possibility for altering the N:P ratio in the sediments is that conditions favorable for volatilization of nitrogen in the lake have increased. Nitrogen volatilization could occur through denitrification ($\text{NO}_2^- \rightarrow \text{N}_2$) or through ammonification ($\text{N}_{\text{org}} \rightarrow \text{NH}_4 \rightarrow \text{NH}_3$), the latter of which is favored under high

pH conditions (Chapra 1997). Elevated pH conditions are well documented in Upper Klamath Lake (Kann and Smith 1999) and have been implicated as a contributing factor in the loss of fish (Perkins et al. 2000).

Another issue of interest with respect to the possible decrease in the N:P ratio in the upper sediments is its relation to effects on community composition of phytoplankton, especially on the cyanobacteria. The greater increase of P in the surficial sediments may lend competitive advantage to various taxa and greatly alter the dominance of the phytoplankton. Based on the data presented here, *Aphanizomenon* were not present in Upper Klamath Lake in the 19th century (it is remotely possible that they were present, but the conditions changed and they began to form akinetes in the 20th century, or that the akinetes exhibit very rapid decomposition rates in these sediments). It is conceivable that the increasing dominance of *Aphanizomenon* in the 20th century may be a consequence of either the increase in P loading or a change in the ratio of N:P. *Aphanizomenon flos-aquae* is capable of fixing nitrogen and presumably would be less affected by direct changes in N availability. However, cyanobacteria such as *Microcystis* are not capable of fixing nitrogen and may be sensitive to both N and P availability.

Another issue relative to nutrients in the sediments that we explored in this study was the concentration of ^{15}N in sediments. This stable isotope of nitrogen has been used to investigate a variety of ecological processes, perhaps most notably as a tracer in freshwater systems for marine-derived N from anadromous fish (cf. Bilby et al. 1996). In these applications, the marine-derived N is recognized by a much higher proportion of $^{15}\text{N}/^{14}\text{N}$. In studies of freshwater systems impacted by large inputs of nonpoint sources of pollution from watershed sources and wastewater, the proportion of ^{15}N is also often elevated (Fry 1999). Denitrification can contribute to substantial enrichment of $\delta^{15}\text{N}$ (Clark and Fritz 1997) as shown in studies of septic tanks (Aravena et al. 1996) and agricultural sources (Bettcher et al. 1990). Although anadromous fish historically passed through Upper Klamath Lake, the magnitude of the runs relative to the size of the lake were far smaller than experienced by systems in Alaska where marine-derived nitrogen is a significant component of the nutrient budget. In Upper Klamath Lake, the large

nutrient contributions from the watershed and the nitrogen fixation derived from cyanobacteria would probably greatly overshadow any historical contributions from anadromous fisheries. The ^{15}N results for Upper Klamath Lake indicate a significant increase in the later part of the 20th century. If salmonids had played a significant role in the nitrogen budget of Upper Klamath Lake, we would have expected to see a decrease in the proportion of ^{15}N corresponding to 1921 when the Copco Dam on the Klamath River prevented salmon from reaching Upper Klamath Lake (KRBFTF 1991). Instead, the proportion of ^{15}N has increased during this period. These results are consistent with an increase in watershed loading of nonpoint sources of nitrogen (Clark and Fritz 1997). An alternative interpretation is that nitrogen fixation from heterocystous cyanobacteria such as *Aphanizomenon flos-aquae* is causing more atmospheric nitrogen to be fixed which would cause the expected ^{15}N ratio in the sediments to approach zero. The potential role of other factors, such as changing water temperatures or selective uptake of heavy nitrogen by aquatic organisms (Adams and Sterner 2000) in altering the sediment ^{15}N cannot be excluded here.

A less ambiguous signal of watershed disturbance is derived from the results of Ti and Al, both of which indicate major increases in erosional inputs to Upper Klamath Lake in the 20th century (Figures 12 and 13). Both metals show major increases above 18cm in the sediment, with Ti peaking at 10 cm and Al peaking at 4 cm. The only alternative explanation for these distributions is that there has been a rapid decrease in deposition of plankton in the 20th century, which would cause the allocthonous inputs to be proportionally greater than the autochthonous inputs. This latter explanation seems highly unlikely given the history of the watershed and the current levels of primary production. We believe that the increase in Ti and Al provide strong evidence of erosional inputs associated with disturbance of the watershed in the 20th century.

Three components of the plankton history in Upper Klamath Lake were investigated: (1) diatoms, (2) *Pediastrum*, and (3) cyanobacteria akinetes. The diatom stratigraphy from Upper Klamath Lake shows changes that were divided into several zones. Although subtle, these changes may represent important changes in environmental conditions.

Zone 1 is dominated by small, benthic *Fragilaria* species. Although small *Fragilaria* taxa are often found in alkaline waters, they have been noted in acidic waters (Krammer and Lange-Bertalot 1991). Frequently, large numbers of these taxa are found in North American lakes immediately following deglaciation (e.g. Smol and Boucherle 1985; Brugam et al. 1988; Wilson et al. 1993; Karst and Smol 2000). It has been suggested that these diatoms may have a competitive advantage in oligotrophic or nutrient-limited waters because they are able to uptake nutrients directly from the sediment water interface (Sheath et al. 1982). It is possible that the large percentages of *Fragilaria* in Zone 1 are indicative of less eutrophic waters at this time. The presence of *Stephanodiscus niagarae*, a diatom typically found in eutrophic waters (e.g. Håkansson and Kling 1989), however, suggests otherwise. The greater abundance of small benthic *Fragilaria* at the bottom of the core may indicate that there were more marshes around or upstream of Upper Klamath Lake at this time. The large decrease in relative abundance of the small *Fragilaria* diatoms at ~59.5cm is consistent with a loss of wetlands in the Upper Klamath Lake catchment area. Research from Ontario indicates that small *Fragilaria* species, specifically *F. construens* and *F. pinnata*, increased as a result of an expansion of the littoral zone due to flooding (Christie and Smol 1996; Karst and Smol 2000).

As well as the decrease in small, benthic *Fragilaria*, Zone 2 is marked by the appearance of *Aulacoseira ambigua*. *Aulacoseira ambigua* is a heavily silicified diatom that forms long chains and requires turbulence to remain in the photic zone. Thus, it is possible that its appearance is related to increased turbulence. A decrease in wetlands in the lakes drainage system could result in a decrease in humic material to the lake and result in increased transparency. A decrease in productivity could also result in increased transparency. However, based on the increased abundances of more eutrophic diatoms, such as *Aulacoseira ambigua* and *Stephanodiscus niagarae*, this does not seem likely.

The appearance of *Asterionella formosa* and *Stephanodiscus hantzschii* at the start of Zone 3 likely indicates increased human activity and increased nutrient availability.

Current diatom seasonality is characterized by spring dominance of small and intermediate-sized *Stephanodiscus* species (*S. parvus*, *S. oregonicus*, and *S. hantzschii*) along with *Asterionella formosa* and occasional *Aulacoseira*, whereas *Stephanodiscus niagarae* increases in the fall (Kann 1988).

Such changes in response to the arrival of Europeans have been noted in numerous studies (cf., Hall et al. 1999). The increase in *Stephanodiscus parvus* may also be related to increased nutrients. The slight decreases in small, benthic *Fragilaria* species may indicate a corresponding decrease in wetlands within the drainage basin of Upper Klamath Lake and/or littoral area of Upper Klamath Lake, which would coincide with European arrival.

The slight decrease in *Aulacoseira ambigua* and *Stephanodiscus niagarae* and coincident increase in *Asterionella formosa* in Zone 3b could indicate: 1) a decrease in available silicon (Si) and/or 2) a decrease in transparency. *Aulacoseira* are heavily silicified diatoms, and are indicated to have high growth requirements for silicon (Kilham et al., 1986). It is expected that *Stephanodiscus niagarae*, also a heavily silicified diatom, would have high silicon requirements. *Asterionella formosa* also require relatively high amounts of silicon for growth (Kilham and Kilham 1978), although their requirements would be expected to be lower than those of *Aulacoseira*. Silicon can become limiting with an increase in phosphorus availability, which can result in decreased diatom production (Schelske and Stoermer 1972). Increased phosphorus concentration in the upper sediments along with increased erosional inputs as indicated by Al and Ti during this same period may reflect such an increase in P availability.

Alternatively, the change in diatom community composition could indicate a decrease in transparency. Owing to their heavily silicified cell walls and the formation of long filamentous colonies, *Aulacoseira* sink quickly out of the photic zone. If available light is decreased, these diatoms are at a competitive disadvantage relative to the lighter and less heavily silicified *Asterionella formosa*. A decrease in transparency could result due to increased humic material from wetland drainage and/or due to increased algal production

in response to increasing nutrients. Given the currently high algal biomass and concomitant high light extinction coefficients due to *Aphanizomenon* blooms ($k > 4 \text{ m}^{-1}$; Kann 1988), increased algal production and silicon limitation due to increased P may both explain the observed species shift.

In addition to the diatoms, one genus of Chlorococcales, *Pediastrum*, is well represented in ancient lake sediments (Hutchinson 1967; Zippi 1998). *Pediastrum* is generally present in nutrient-rich lakes and is often associated with other taxa found in nutrient lakes such as *Anacystis*, *Anabaena*, *Melosira*, and *Fragilaria crotenensis* (Hutchinson 1967). The abundance of *Pediastrum* remains in the sediments of Upper Klamath Lake support the view that the lake has been highly productive for a long period. This is consistent with *Pediastrum* seasonally succeeding diatoms in enriched, physically variable lakes with high ratios of mixed depth to euphotic depth (Reynolds 1984). However, a decrease in the relative proportion of *Pediastrum* does not indicate a decrease in productivity of the system. The increase in lake sediment nutrients clearly indicates that the lake has not become less productive. Rather, the decrease in *Pediastrum* is likely the consequence of a further advancement in the productivity of the lake thus allowing other taxa to more effectively compete.

Although some diatom taxa have made new appearances (*Asterionella formosa*, Figure 15) or substantial increases (*Stephanodiscus parvus*; *S. hantzschii*, Figures 15 and 16) in Upper Klamath Lake, the most noteworthy change in phytoplankton composition is the appearance and current dominance of the cyanobacterium, *Aphanizomenon flos-aquae* (Figure 19). During the summer, biomass of the organism typically reaches 50 mg L^{-1} wet wt. or $>250 \text{ } \mu\text{g L}^{-1}$ chlorophyll *a* (Kann 1988). Because *Aphanizomenon* generally requires high P levels to dominate (Sommer 1989; Pechar 1992), and has a competitive advantage at lower N:P ratios (*cf.* Smith 1983), the complete absence of *Aphanizomenon* akinetes in sediments deeper than 20 cm and its transition to the dominance it exhibits today is consistent with the observed sediment changes in these parameters (see above). Thus, the appearance and continual expansion of *Aphanizomenon* is perhaps the most striking evidence in the sediments to support the view that the water quality and

biological community in Upper Klamath Lake has been seriously altered in the 20th century.

There is always some concern that when most of the analyses is confined to a single core, the results could be an artifact of atypical patterns from that specific sediment sample. We believe that there are several lines of evidence supporting the patterns we observed in core K1. First, is that our dating sequence was repeated elsewhere in core K3 located several kilometers from the location of core K1. Second, the dating sequences we observed in both cores were similar to the results obtained by Colman et al. (1999). Third, the patterns we observed for *Pediastrum*, the *Aphanizomenon* akinetes, and Ti were nearly identical to those observed by Bradbury and Colman (unpublished data, core C7-A). Note that where we measured elemental Ti as an erosional indicator, Bradbury and Colman reported tephra (Figure 21).

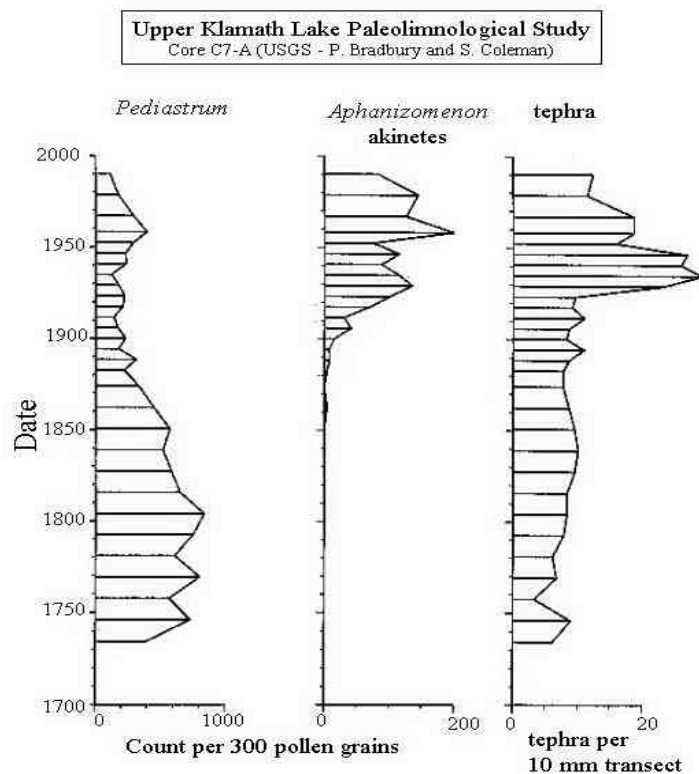


Figure 21. *Pediastrum* counts, *Aphanizomenon* akinetes, and tephra measured in core C7-A from Upper Klamath Lake (Source: P. Bradbury and S. Colman, USGS, unpublished data).

CONCLUSIONS

Upper Klamath Lake, for at least the period of record represented by this study (~ 1000 yr), has been a very productive lake. The diatom stratigraphy shows a diverse assemblage of taxa typically found in eutrophic and hypereutrophic lakes. Cyanobacteria have been present throughout this period and nutrient concentrations in the sediment have been high. Nevertheless, the recent sediments show a coherent record of higher nutrient concentrations, decreased molar ratios of N:P, elevated erosional inputs, higher rates of sediment accumulation, and appearance of phytoplankton taxa previously unseen in the lake. The new phytoplankton are without exception indicative of extremely productive waters. Although mixing of the uppermost sediments precludes high-resolution analysis of temporal changes in Upper Klamath Lake, the magnitude and direction of the signal is unambiguous.

ACKNOWLEDGEMENTS

This work was supported by the US Bureau of Reclamation through contract **9-FG-20-17730** to JC Headwaters, Inc. We gratefully acknowledge the assistance of our project officer, Mr. Mark Buettner of the Klamath Falls office. We are indebted to Drs. Platt Bradbury and Steve Colman for providing access and permission to cite their unpublished data.

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